

Combustion Processes in Hybrid Rocket Engines

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In recent years, there has been a resurgence of interest in the development of hybrid rocket engines for advanced launch vehicle applications. Hybrid propulsion systems use a solid fuel such as hydroxyl-terminated polybutadiene (HTPB) along with a gaseous/liquid oxidizer. The performance of hybrid combustors depend on the convective and radiative heat fluxes to the fuel surface, the rate of pyrolysis in the solid-phase and the turbulent combustion processes in the gaseous-phase. These processes in combination specify the regression rates of the fuel surface and thereby the utilization efficiency of the fuel. In this paper, we employ computational fluid dynamic techniques in order to gain a quantitative understanding of the physical trends in hybrid rocket combustors.

The computational modeling is tailored to ongoing experiments at Penn State that employ a 2D slab-burner configuration. The co-ordinated computational/experimental effort enables model validation while providing an understanding of the experimental observations. Computations to date have included the full-length geometry with and without the aft-nozzle section as well as shorter-length domains for extensive parametric characterization. HTPB is used as the fuel with 1,3 butadiene being taken as the gaseous product of the pyrolysis. Pure gaseous oxygen is taken as the oxidizer. The fuel regression rate is specified using an Arrhenius rate reaction, while the fuel surface temperature is given by an energy balance involving gas-phase convection and radiation as well as thermal conduction in the solid-phase. For the gas-phase combustion, a two-step global reaction set is used. The standard $k - \epsilon$ model is used for turbulence closure. Radiation is presently treated using a simple diffusion approximation which is valid for large optical path lengths, representative of radiation from soot particles.

Computational results are obtained to determine the trends in the fuel burning or regression rates as a function of the head-end oxidizer mass flux, $G = \rho_e U_e$, and the chamber pressure. Furthermore, computations of the full slab-burner configuration have also been obtained for various stages of the burn. Comparisons with available experimental data from small-scale tests conducted by General Dynamics-Thiokol-Rocketdyne suggest reasonable agreement in the predicted regression rates. Future work will include: (1) a model for soot generation in the flame for more quantitative radiative transfer modeling, (2) parametric study of combustion efficiency and (3) transient calculations to help determine the possible mechanisms responsible for combustion instability in hybrid rocket motors.

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Presentation Outline

- Introduction
 - Research Issues
 - Penn State Slab Burner Configuration
- Physical Modeling
 - Gas/Surface Coupling
 - Radiation
- Computational Results
 - Representative Solutions
 - Characterization of Regression Rates
- Conclusions

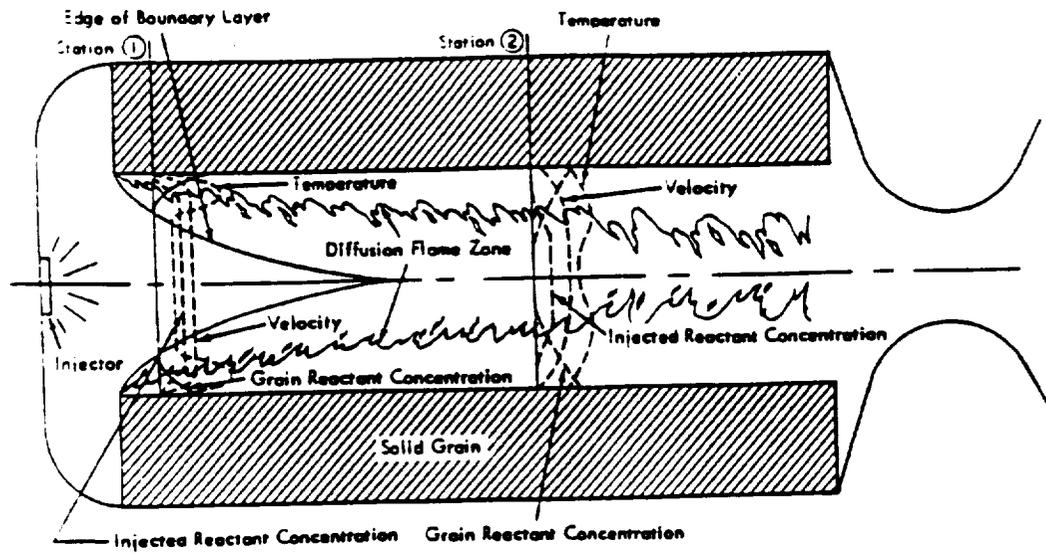
Introduction

- Advantages of Hybrid Propulsion
 - Reduced Cost
 - Safety
 - Improved Reliability
 - Thrust Tailoring
 - Environmentally Friendly
- Hybrids Development
 - Intermittent Testing Since 60's
 - JIRAD
 - AMROC
 - France & Japan
- Small-Scale Testing
 - JPL/Strand *et al.*
 - ONERA
 - UAH
 - Penn State

Research Issues

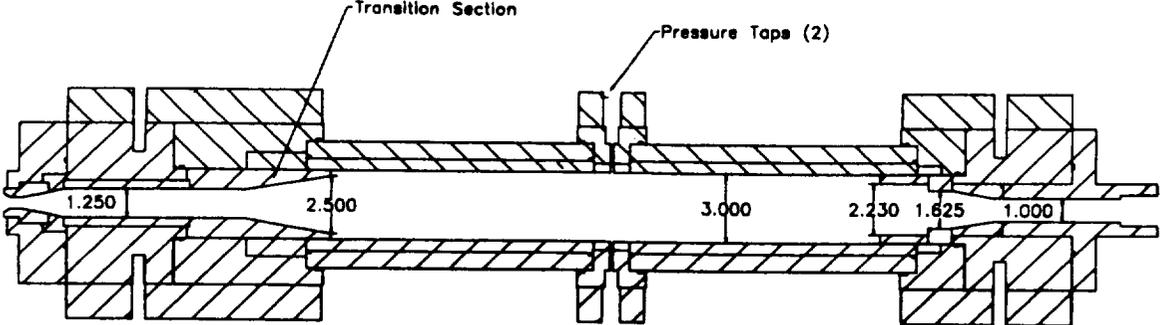
- Characterization of Fuel Surface Regression
 - Fuel Pyrolysis and Surface Chemistry
 - Heat Fluxes - Convection and Radiation
- Combustion Efficiency
- Combustion Instability
- Modeling Issue:
 - Boundary Layer vs. Navier-Stokes

Schematic of Hybrid Rocket Motor

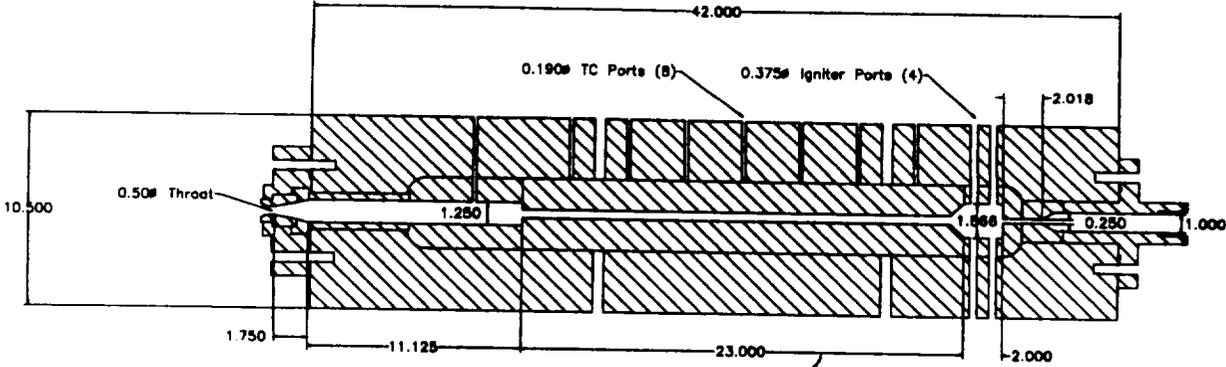


Experimental Configuration

Top View



Profile View

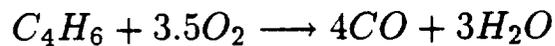


Experimental Configuration

- Test Conditions
 - Fuel - HTPB
 - Oxidizer - GOX
 - Pressures - 300 to 900 psi
 - GOX Flow Rates - 0.2 to 0.8 lbm/s
 - GOX Mass Flux ($G = \rho U$) - ~~0.1 to 0.5~~^{0.1} to 0.5 $lbm/in^2 - s$

Physical Modeling

- Gas-Phase Navier-Stokes Equations
 - Standard $k - \epsilon$ Model
- Gas-Phase/Combustion Model:
 - Butadiene—Product of Pyrolysis
 - Two-Step Global Kinetics Model



- Solid-Phase/Pyrolysis:
 - Arrhenius Pyrolysis Rate

$$\rho_s r_b = A_s \exp\left(\frac{-E_s}{R_u T_s}\right)$$

Solid/Gas Coupling

- Surface Mass Balance

$$\rho v = - \rho_s r_b$$

- Surface Energy Balance

$$-\lambda \frac{\partial T}{\partial y} + Q_{rad} + \rho v h - \sum_{i=1}^N \rho D_{im} \frac{\partial Y_i}{\partial y} h_i = -\lambda_s \left(\frac{\partial T}{\partial y} \right)_s - \rho_s r_b h_s$$

Radiation Modeling

- Gaseous Molecular Radiation
 - Optically Thin Approximation

$$Q_{rad,k} = \sum_{i,j} \frac{4\sigma k_{i,j} T_{i,j}^4}{J_{i,j}} \mathcal{F}_{i,j \rightarrow k}$$

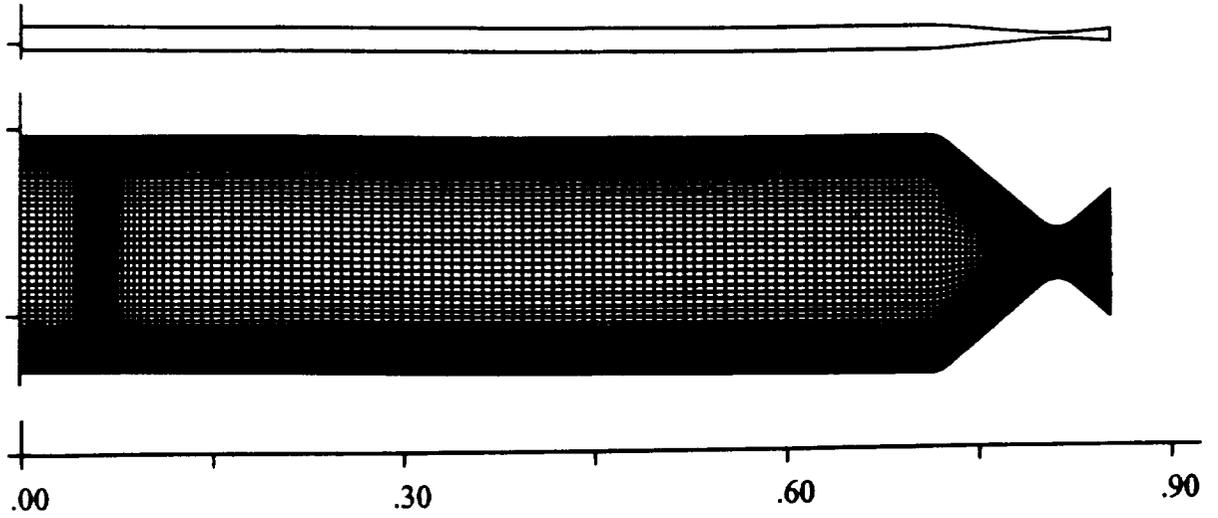
- Particulate (Soot) Radiation
 - Optically Thick Approximation

$$Q_{rad,k} = -\lambda_R \frac{\partial T}{\partial y}$$

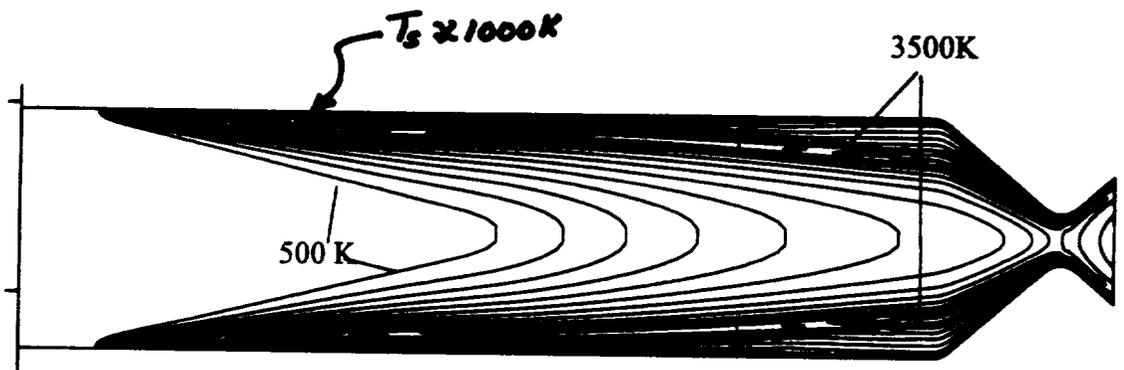
where $\lambda_R = \frac{4}{3} \pi \frac{C}{k} T^3$

Representative Solution

Grid Geometry

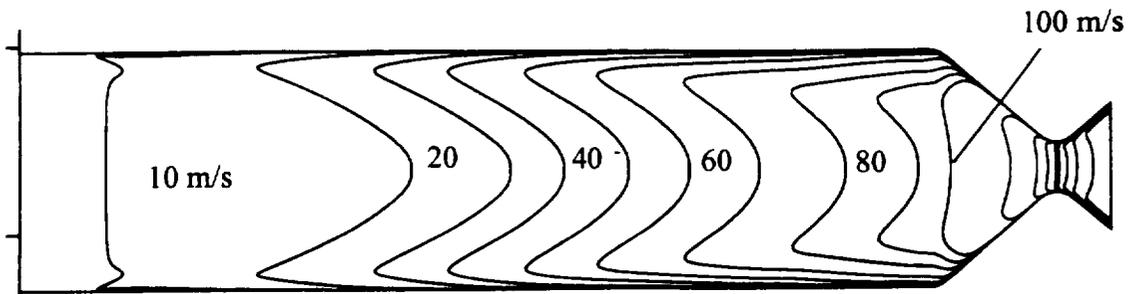


Temperature Contours

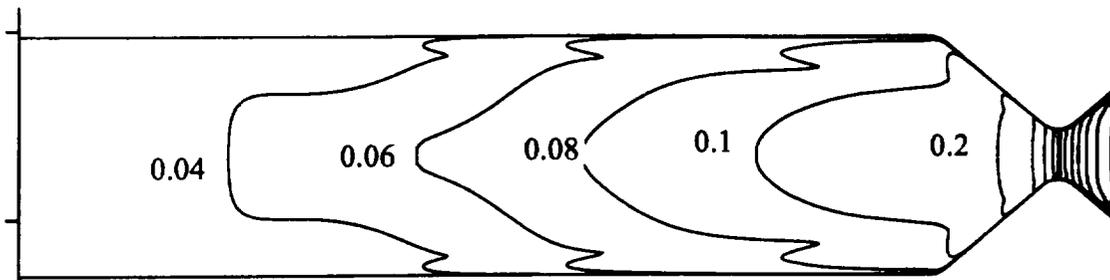


Representative Solution

Axial Velocity



Mach Number Contours

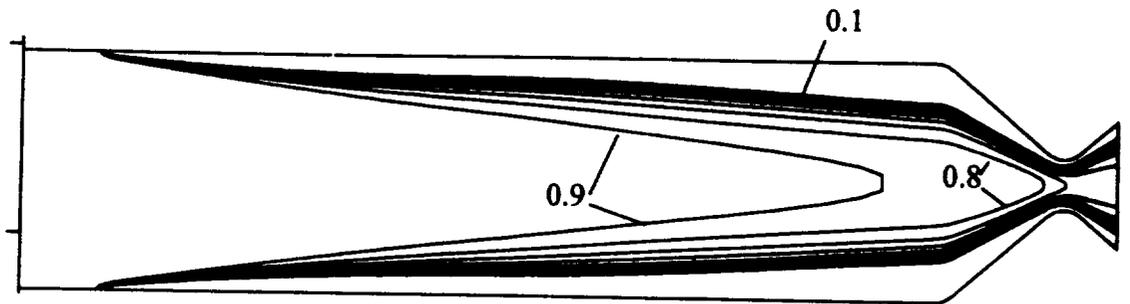


Representative Solutions

Carbon Dioxide Mass Fraction

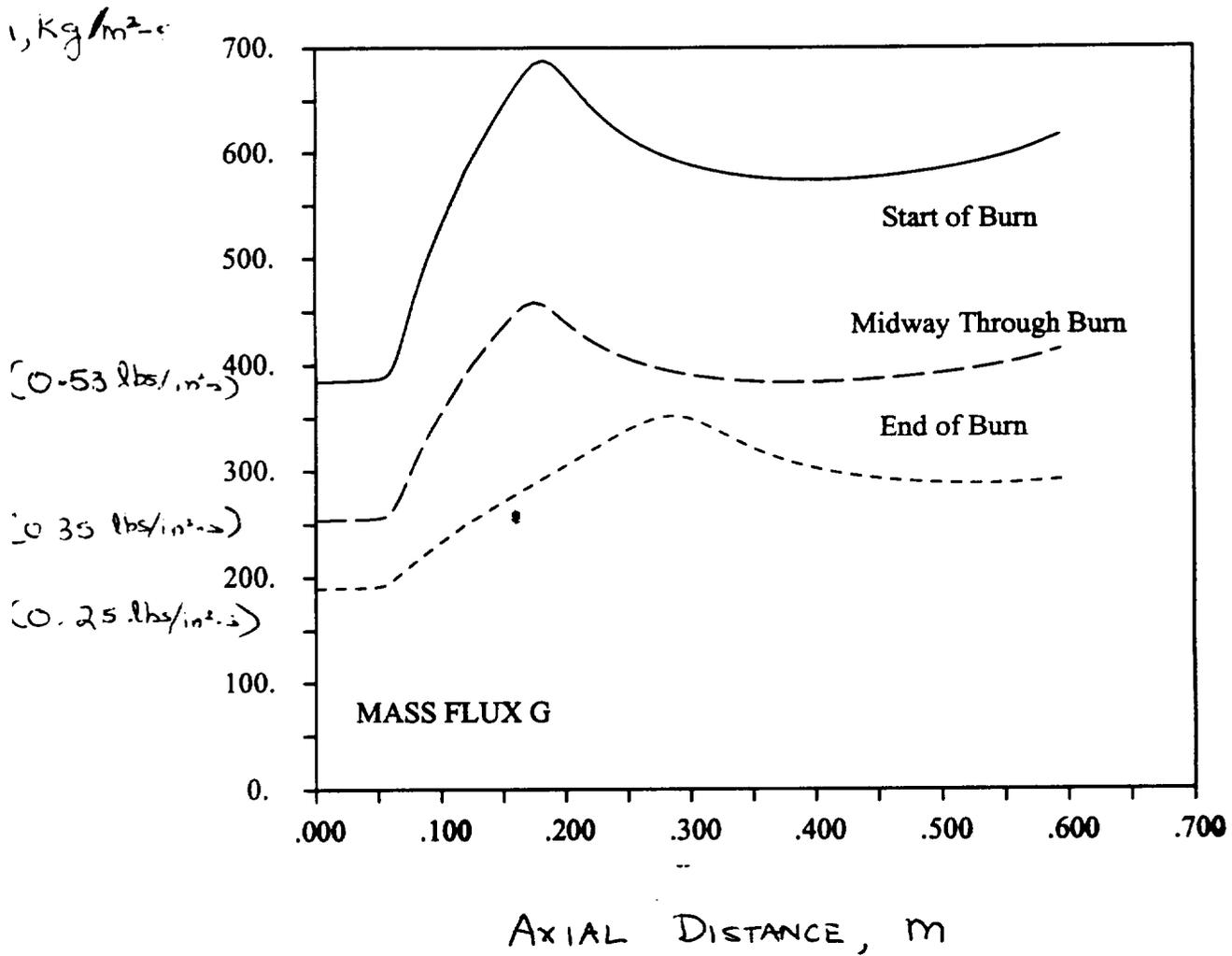


GOX Mass Fraction



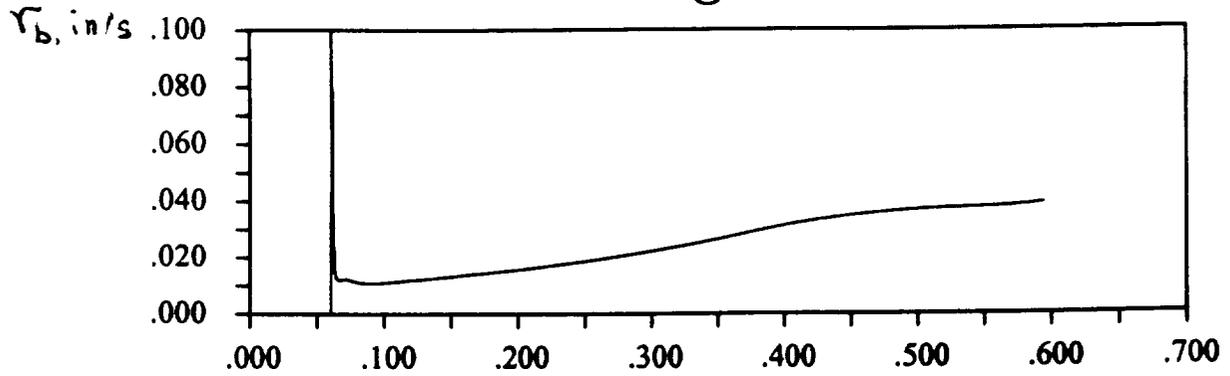
Representative Results

Centerline Variation of Mass Flux (G)

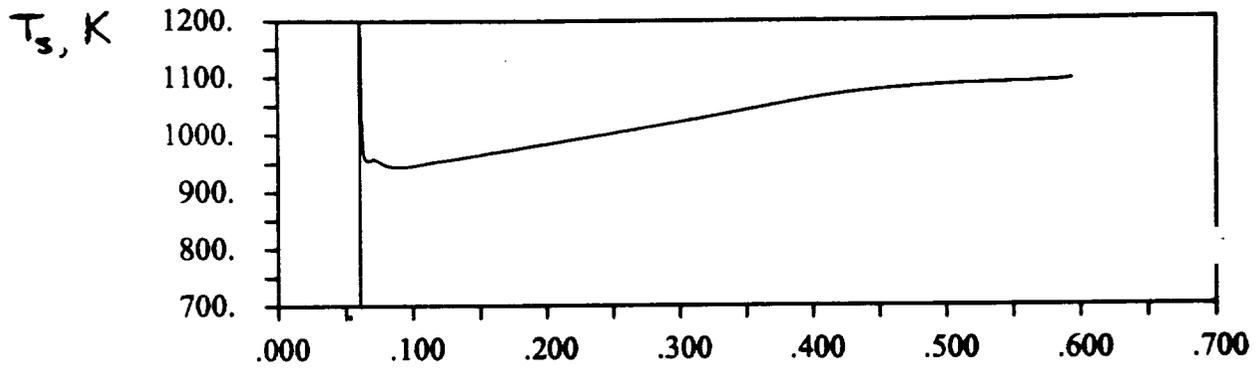


Representative Results

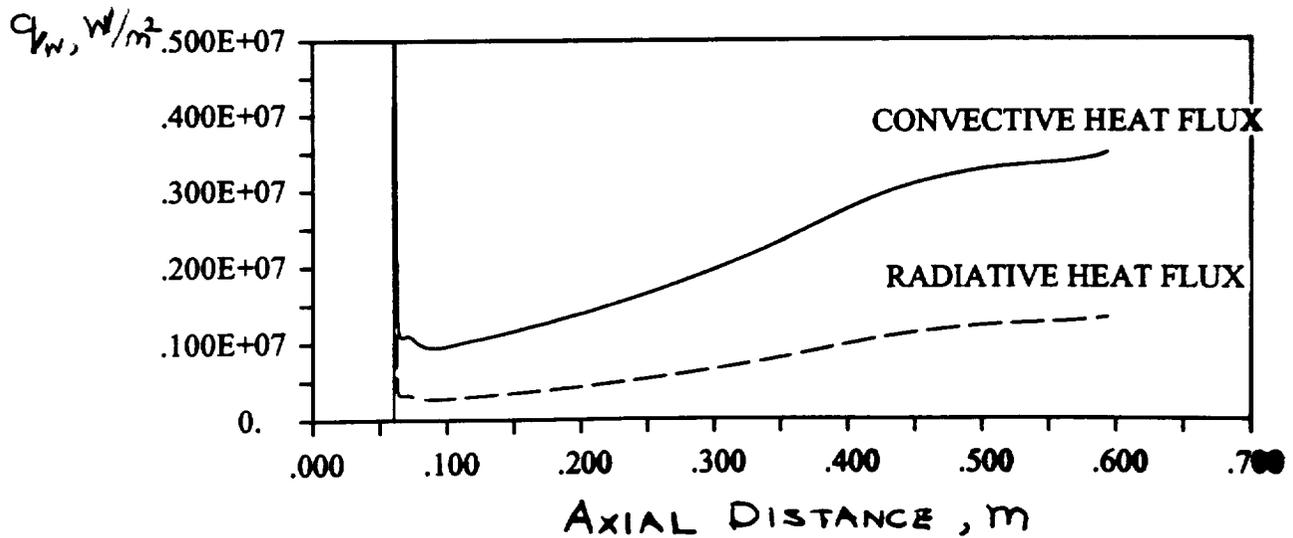
Surface Regression Rate



Fuel Surface Temperature



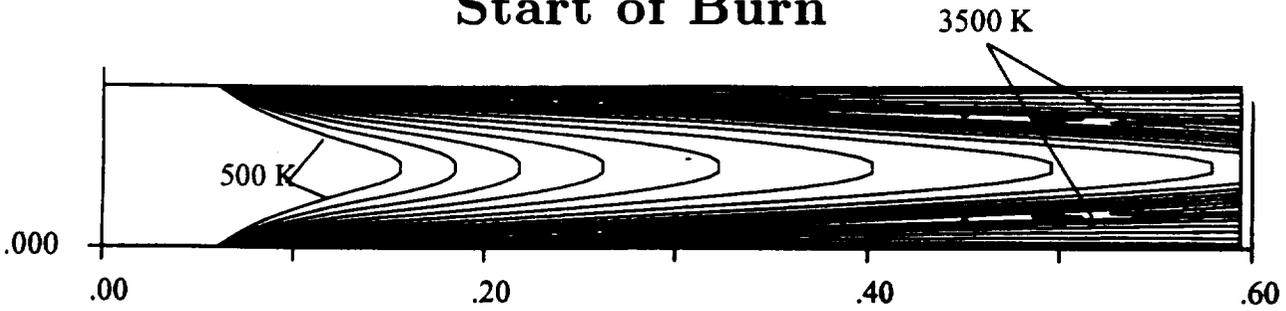
Wall Heat Fluxes



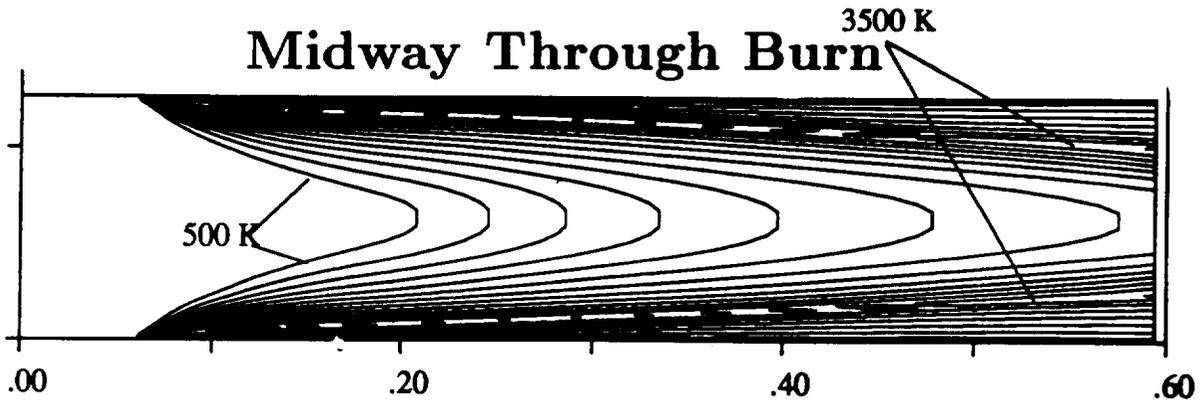
Parametric Studies

Different Stages in Burn

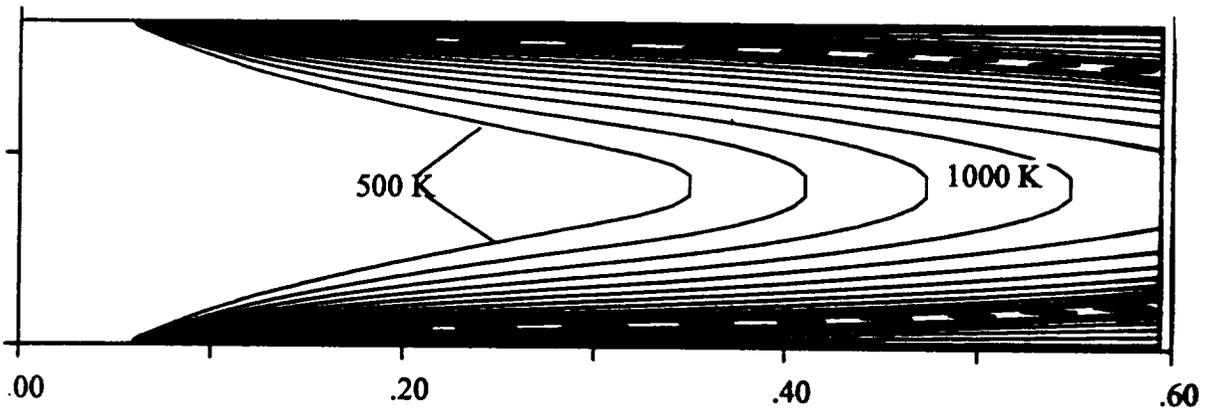
Start of Burn



Midway Through Burn



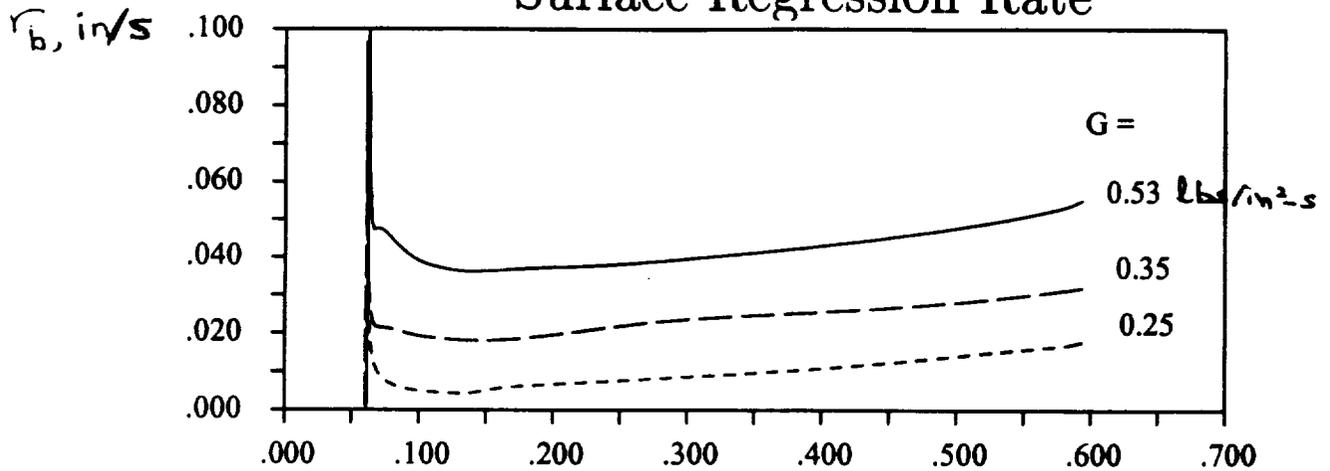
End of Burn



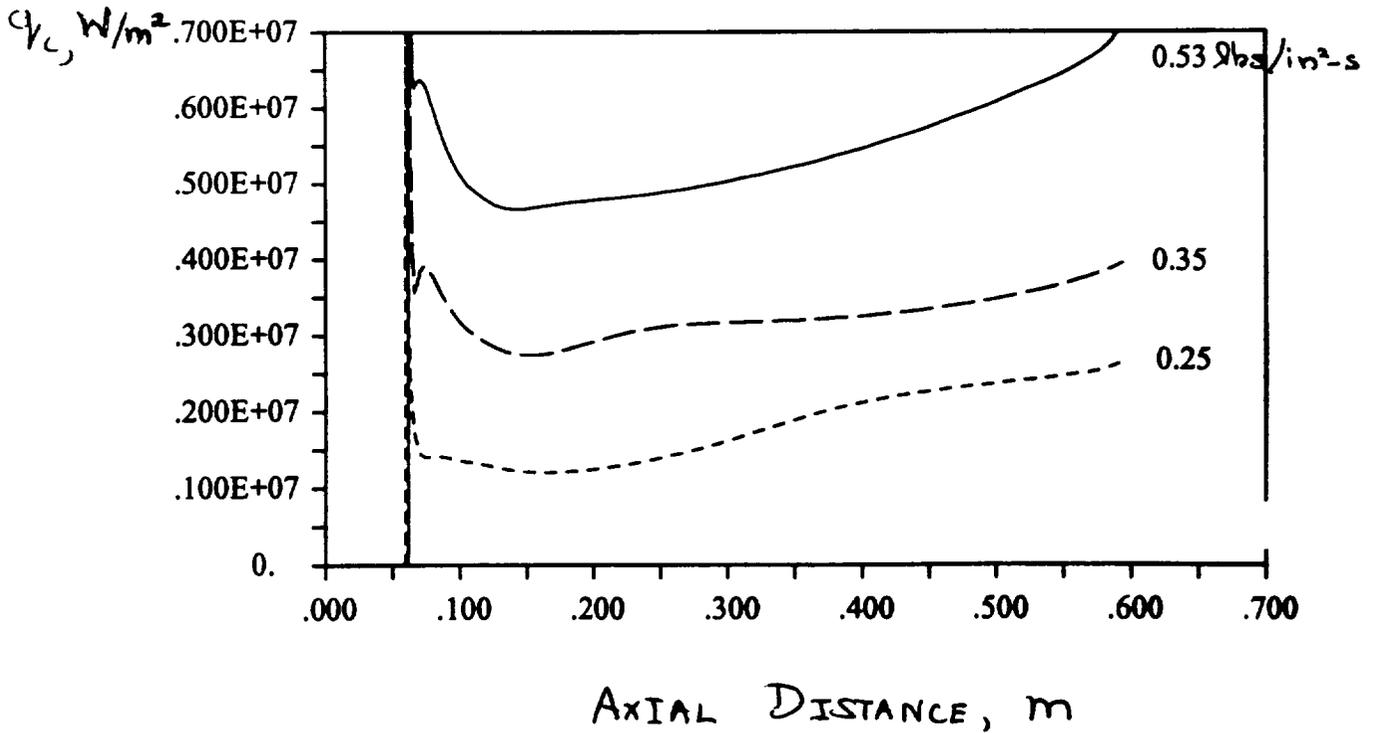
Parametric Studies Different Stages in Burn

W/O Radiation

Surface Regression Rate



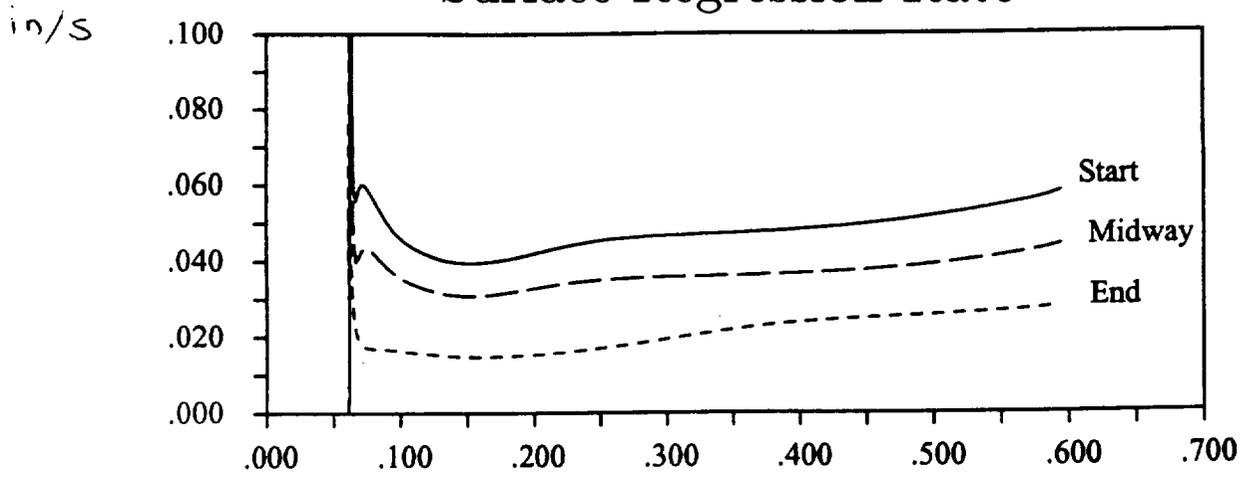
Convective Wall Heat Fluxes



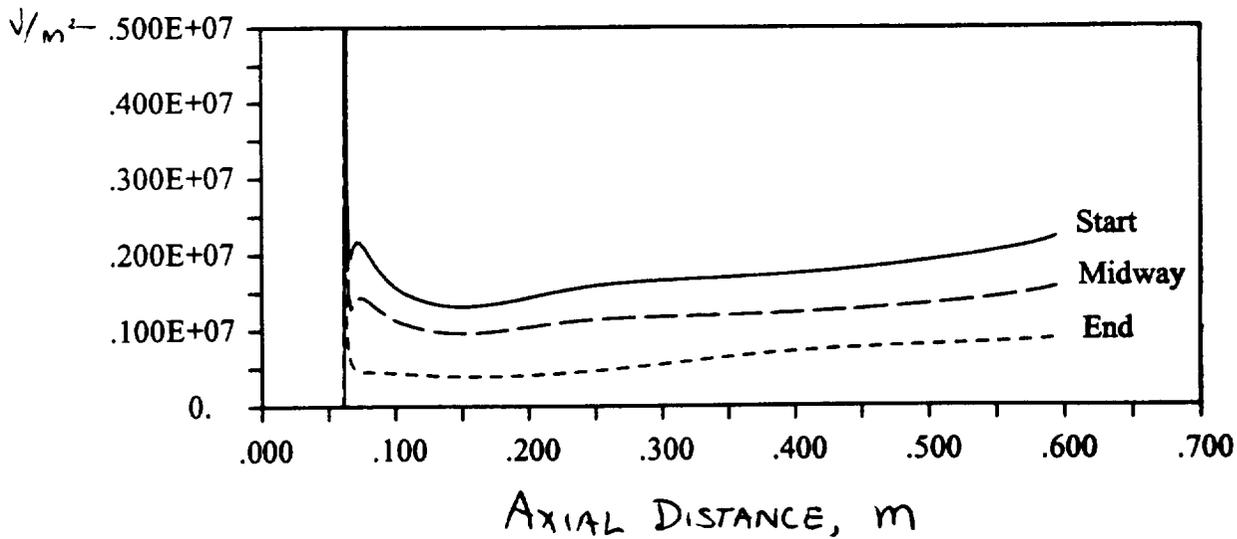
Parametric Studies Different Stages in Burn

With Radiation/Optically Thick

Surface Regression Rate

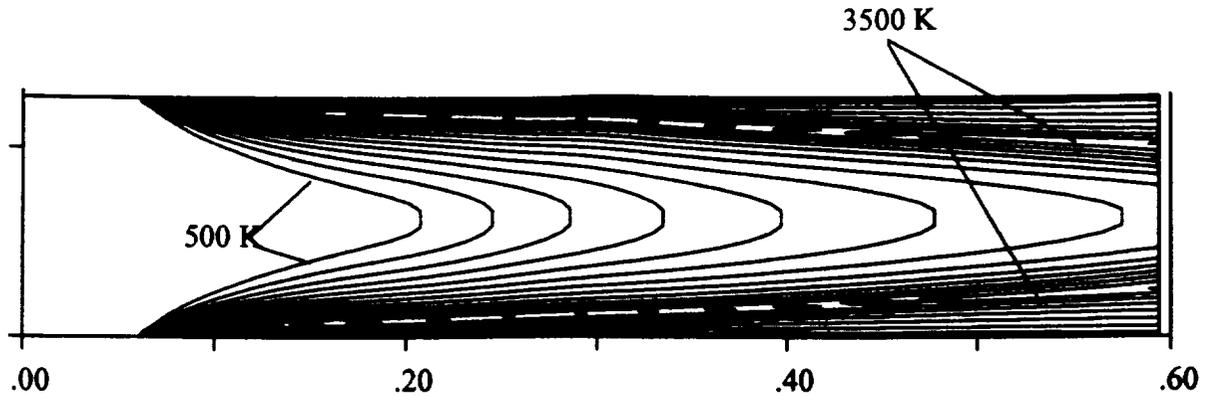


Radiative Wall Heat Fluxes

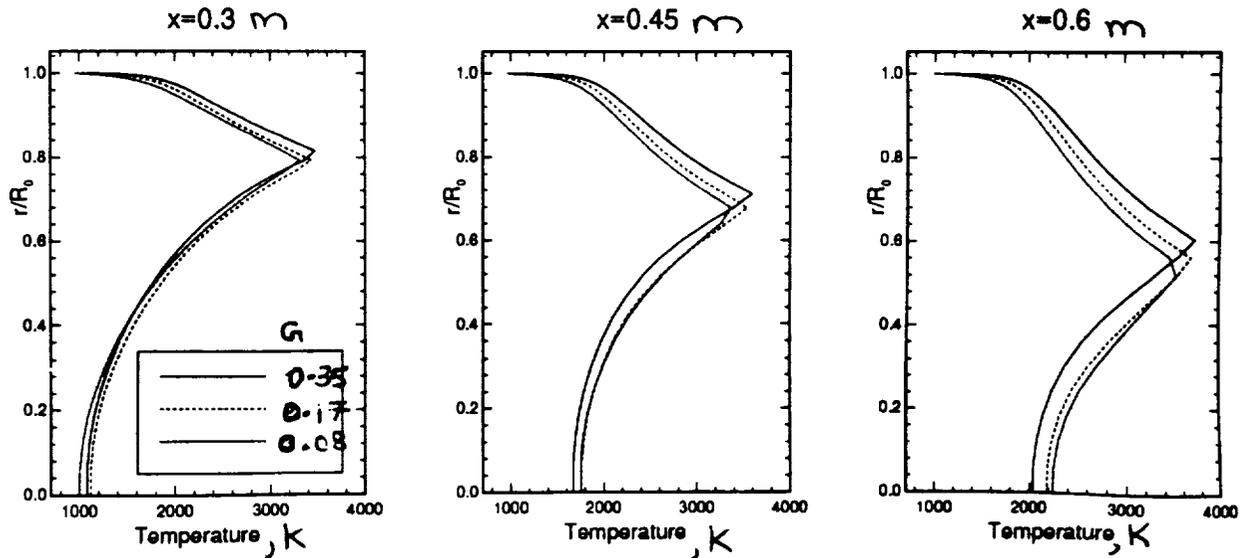


Parametric Studies Effect of GOX Flow Rate

Temperature Contours



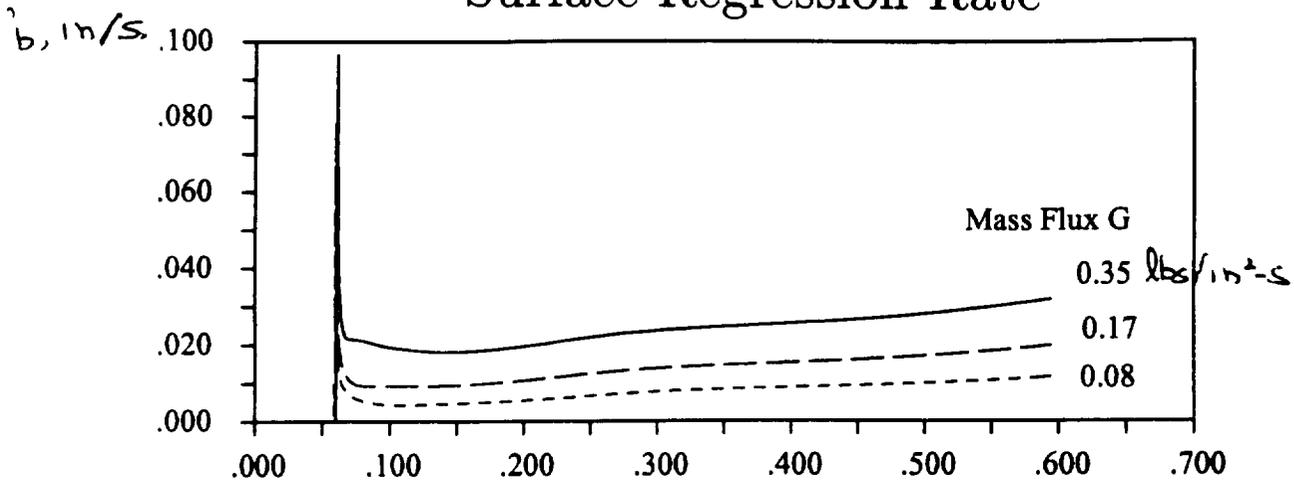
Temperature Profiles



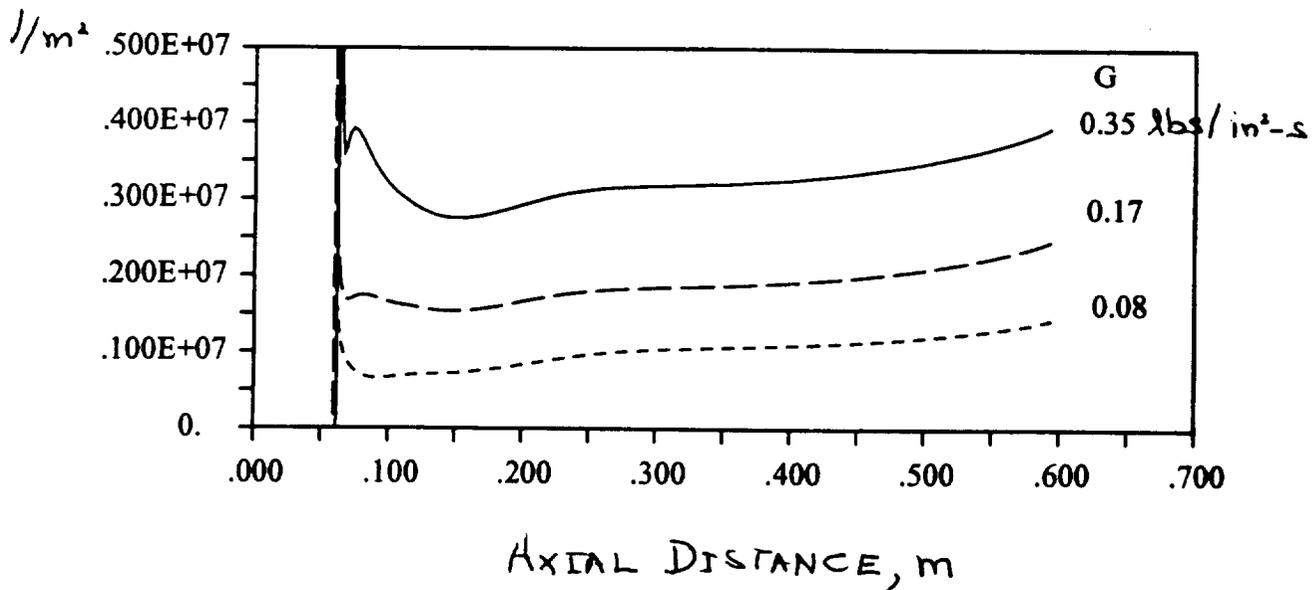
Parametric Studies Effect of GOX Flow Rate

W/O Radiation

Surface Regression Rate



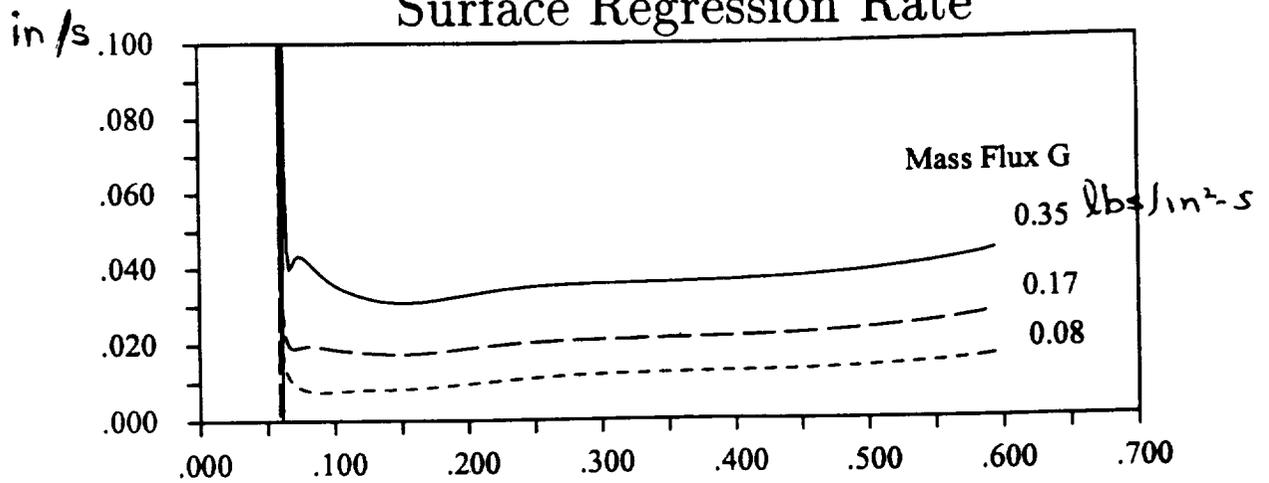
Convective Wall Heat Fluxes



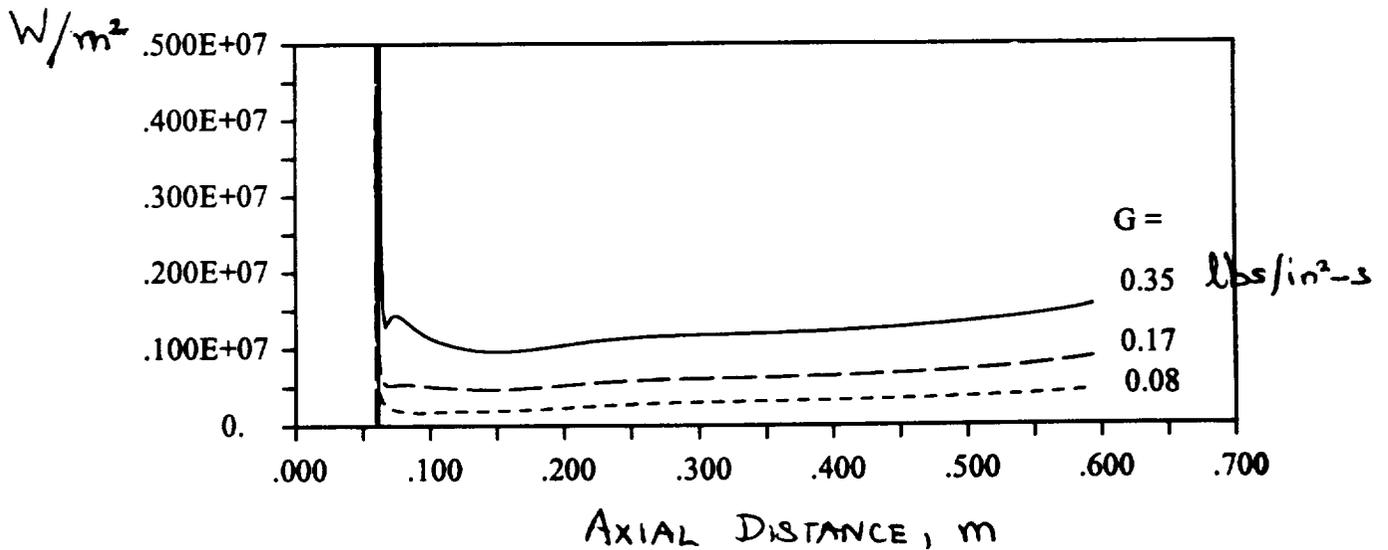
Parametric Studies Effect of GOX Flow Rate

With Radiation/Optically Thick

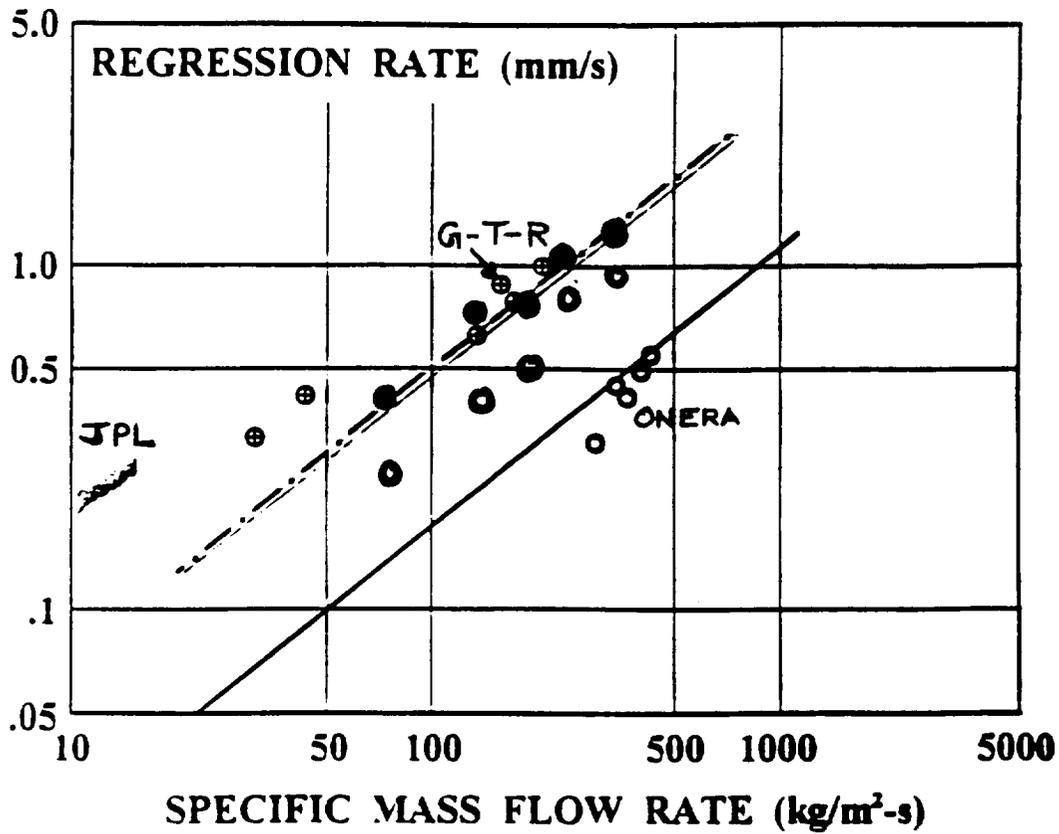
Surface Regression Rate



Radiative Wall Heat Fluxes



Parametric Characterization of Fuel Surface Regression



- Current Results With Radiation
- Current Results W/o Radiation

Conclusions

- Navier-Stokes Analysis of Hybrid Motor
 - Planar Slab Burner Configuration
 - Arrhenius-Rate for Pyrolysis
 - Global Chemistry
 - Turbulence Model
 - ‘Thick/Thin’ Radiation Model
- Computational Results
 - Parametric Characterization
 - Fuel Surface Temperatures 900 to 1100 K
 - Regression Rates of 0.01 to 0.07 in/s
 - Radiative Fluxes - Significant Contribution
- Ongoing/Future Work:
 - Radiation Properties - Soot Concentration
 - Combustion Efficiency - Downstream Mixing
 - Combustion Instability - Transient Calculations